# SOME ASPECTS OF FENITIZATION WITH PARTICULAR REFERENCE TO CHILWA ISLAND AND KANGANKUNDE, MALAWI

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## SYNOPSIS

A general petrological account is given of the process of fenitization at the carbonatite complexes of Chilwa Island and Kangankunde. Twelve whole rock analyses are presented and the chemical changes occurring during fenitization are discussed in the light of these new data, together with published data from other complexes. Particular emphasis is placed on the use of the triangular diagram quartz–nepheline–kalsilite for following the changes in the felsic constituents during fenitization of granitic rocks, and for displaying the chemical differences between the processes of fenitization, potash-feldspathization, and nephelinization. The possible relationship between these processes and carbonatite emplacement is discussed, and it is suggested that there is probably an evolutionary series of carbonatites having strongly contrasting metasomatizing powers. It is pointed out that most fenite occurrences can be linked with silicate magmas, and that fenites which are undoubtedly attributable to the action of carbonatite are rare.

## INTRODUCTION

THE Chilwa Province of Southern Malawi comprises a series of volcanic vents, which are filled with carbonatite, feldspathic breccia, agglomerate and nepheline syenite, plugs of syenite and nepheline syenite, and an associated dyke suite of solvsbergite, trachyte, microfoyaite, phonolite and nephelinite. (Garson 1965*b*, p. 12) (Text-fig. 1.) The province appears to be Upper Jurassic to Lower Cretaceous in age (Bloomfield, 1965), and is associated, in a broad sense, with the rift system. These rocks were first described in the classic bulletin of Dixey, Campbell Smith & Bisset (1937), and they recognized the intrusive nature of the limestone on Chilwa Island, the first carbonatite to be described from Africa. The Malawi carbonatites have, in recent years, been investigated and described in great detail by Garson (1962, 1965*a*, 1965*b*; and numerous other papers) and Garson & Campbell Smith (1958). The Chilwa Island and Kangankunde vents are well suited to a study of fenitization because of the broad extent of their aureoles, but are restricting in so far as the outer limits of the Chilwa aureole are concealed beneath the lake, while the outer zones of fenitization at Kangankunde are poorly exposed. At both localities a group of potash-rich rocks, mapped as feldspathic breccia and contact breccia by Garson at Chilwa Island (1958, Map 2) and as feldspathic breccia and agglomerate at Kangankunde (1965*a*, Map 2), lie between the carbonatites and the fenites, and these rocks are characteristic of many of the Chilwa Province carbonatite complexes. They have been shown to be derived from the more normal fenites by a process of potash metasomatism (Garson & Campbell Smith, 1958, p. 30; Garson, 1965*a*, p. 37). These potash-rich rocks, as well as the more typical fenites, are included in this study. At neither locality do extensive bodies of intrusive silicate rocks occur, although small plugs and dykes of nepheline syenite, ijolite, trachyte, nephelinite, solvsbergite and alnoite are found at Chilwa Island (Garson & Campbell Smith, 1958) and a few dykes of solvsbergite and alnoite have been emplaced at Kangankunde (Garson, 1965a).

The fenitization at both these localities has already been described (op. cit. 1958, p. 28) so that the field and petrographic data presented in this account will be of a general nature and a stress will be put on new observations. As well as over 300 specimens collected by me, use has been made of the thin-sections in the collection of the British Museum (Natural History), made for Dr. Campbell Smith from

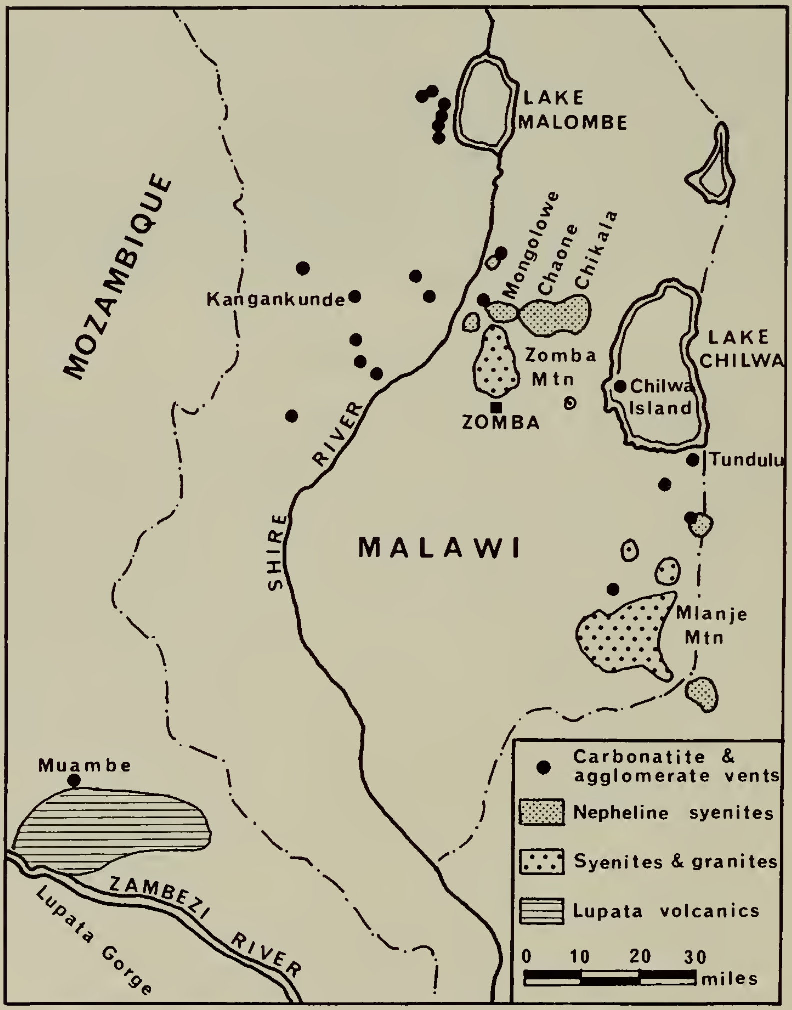



Fig. 1. Distribution of the rocks of the Chilwa Alkaline Province in Southern Malawi. Map based in part on map of Garson (1966, fig. 1).

material collected by Dixey & Garson. No petrochemical data of the fenites of Chilwa Island or Kangankunde have been published heretofore.

## PETROLOGY

### *Chilwa Island*

Geologically, Chilwa Island is built of a central core of carbonatite which is surrounded by a collar of feldspathic breccia and this in turn is surrounded by a group of fenitized schists and syenites. A simplified geological map, taken from Garson & Campbell Smith (1958) is given as Text-fig. 2. Garson has distinguished and mapped three types of carbonatite, while he divides the fenitized basement into a group of granulites and a series of older intrusive syenites (op. cit. 1958, map 2). The granulites vary from quartzo-feldspathic schists through to pyroxene and hornblende-quartz-feldspar types, and limestones, amphibolites, pyroxene schists and rocks of charnockitic affinities also occur. The syenites are coarse rocks, usually of a porphyritic habit.

The fenitized rocks are characteristically net veined and display a greenish hue, features described from many fenite localities, while the feldspathic breccias are red or cream in colour and distinctly more leucocratic. No contacts between the fenite and the feldspathic breccia can be seen. From a study of the thin sections it is possible to distinguish two main types among the fenites, a less fenitized group of quartz fenites and an inner group of syenitic fenites. The distribution of the two types is brought out in Text-fig. 3A. The quartz fenites are distinguished in thin section by a mineralogy inherited primarily from the basement including plagioclase (oligoclase to andesine), orthoclase, hornblende, ortho- and clino-pyroxene, biotite and quartz. The syenitic fenites, in contrast, are dominated by a new mineralogy of perthite, aegirine, minor alkaline amphibole and secondary biotite; quartz is now rare. The feldspathic breccias are formed dominantly of potash-feldspar and ore, with minor zircon, although commonly they contain quartz, the result of late silicification. The range of minerals in the fenites is as follows:

| | Country rocks | Quartz fenites | Syenitic fenites | Feldspathic breccia |
|---|---|---|---|---|
| *PRIMARY MINERALS* | | | | |
| Hornblende, ortho, clino-pyroxene, ore and biotite | ——— | ——— | - - - | |
| Plagioclase and orthoclase | ——— | ——— | - - - | |
| Quartz | ——— | ——— | - - - | |
| *SECONDARY MINERALS* | | | | |
| Aegirine | | ——— | ——— | |
| Riebeckitic amphibole | | ——— - - | | |
| Magnesioarfvedsonitic amphibole | | - - ——— | ——— | |
| Secondary biotite | | ——— | ——— | |
| Ore | | ——— - - - | | ——— |
| Perthite | | ——— | ——— | - - - |
| Orthoclase | | | | - ——— |
| Quartz | | | | ——— |

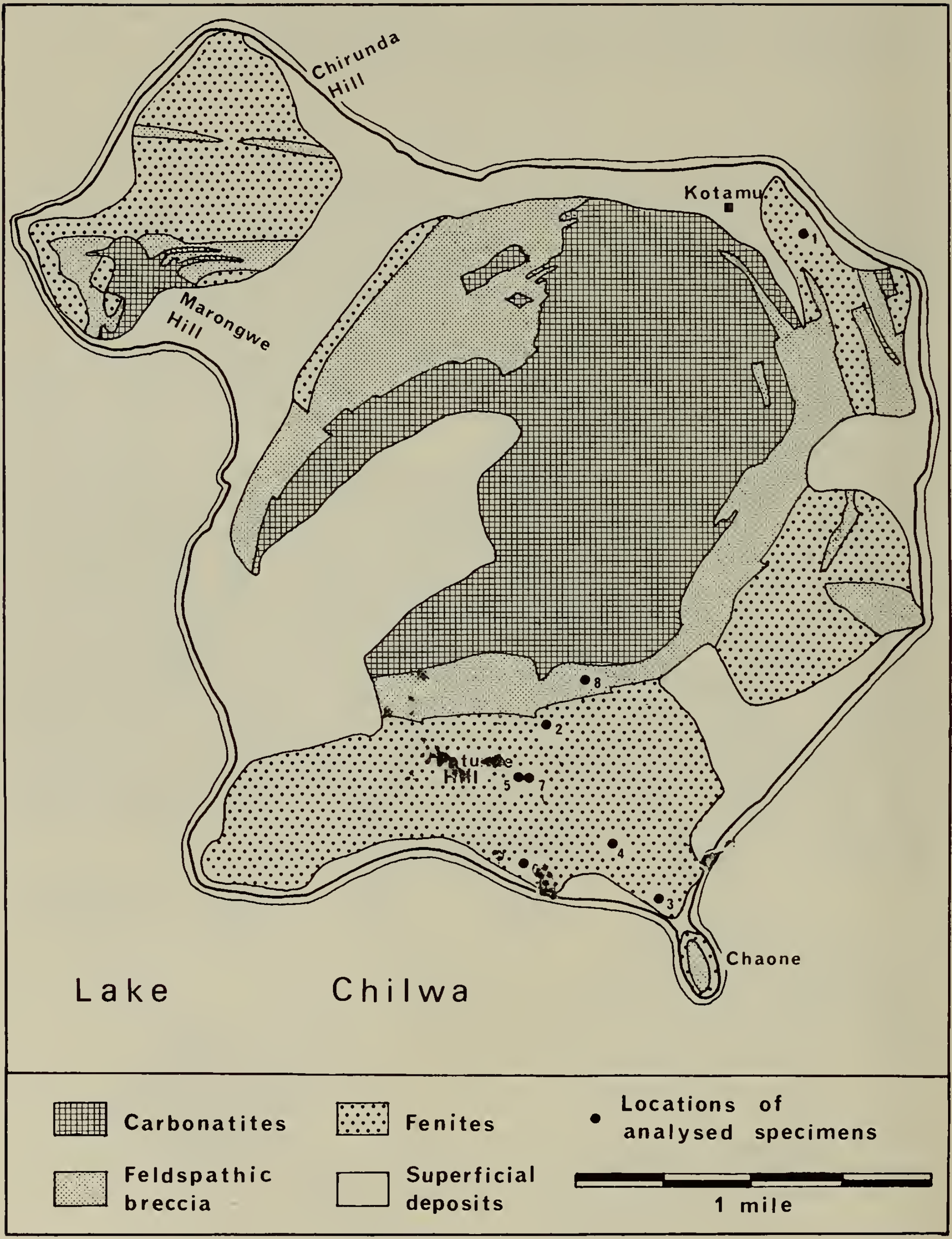



FIG. 2. The geology of Chilwa Island. Based on map of Garson & Campbell Smith (1958, fig. 9). The locations of the analysed specimens are indicated.

The change from the quartz fenites to the syenite fenites is vigorously promoted through the microscopic network of cracks, which develops early in the fenitization process, and along the length of the fine network of "fenite" veins which later form along these cracks. Quite quickly the rock along, and immediately adjacent to, the veins, by the growth of aegirine and alteration of the feldspar, becomes a syenitic fenite, and by the pervasion of these changes through the whole rock the syenitic fenite stage is reached. The alteration of the syenitic fenites to the feldspathic breccias is also promoted through the agency of the fenite veins in so far as the alteration of the aegirine, amphibole, and biotite to ore minerals first takes place along the veins, and eventually the rock is reduced to potash feldspar with a fine vein system defined by the ore which pseudomorphs the characteristic veins of the syenitic fenites.

The sequence of mineralogical changes which have been observed to take place in the alteration of the basement schists and syenites into the syenitic fenites are as follows:

| PRIMARY MINERALS | | SECONDARY MINERALS |
|---|---|---|
| Hornblende | ⟶ | aegirine ± magnetite ± biotite ± alkaline amphibole |
| Hornblende | ⟶ | biotite (magnetite) ⟶ aegirine |
| Biotite | ⟶ | aegirine ± alkaline amphibole |
| Ore | ⟶ | alkaline amphibole |
| Clino-pyroxene | ⟶ | aegirine |
| Ortho-pyroxene | ⟶ | riebeckitic amphibole |
| Quartz | ⟶ | aegirine |
| Plag. and orthoclase | ⟶ | perthite ± plagioclase ± microcline |

The alteration of hornblende to aegirine often involves an intermediate stage of biotite, and sometimes magnetite, growth and in the case of biotite a very thin rim of an unidentified feldspar usually intervenes between the mica and the replacing aegirine. The secondary biotite is itself replaced by aegirine, but it persists throughout the syenitic fenite zone. It is pale to medium brown in colour and probably has a high ferric to ferrous iron ratio as reported from Alnö (von Eckermann, 1948, p. 32). Aegirine is the most widespread and characteristic new mafic mineral in the fenites. It develops at the expense of hornblende, biotite and pyroxene and replaces quartz, often by the formation of a peripheral corona of radiating prisms which gradually encroach inwards. Aegirine also grows as isolated grains and decussate and radiating clusters along the length of the " fenite " veins; indeed these veins are commonly built solely of aegirine. With increasing fenitization the aegirine aggregates recrystallize to form much larger individual grains. The colour of the aegirine varies from a deep blue-green to deep emerald-green through to buff or almost colourless, and radiating clusters are often colour zoned, invariably with the colour intensity increasing outwards. Optical properties do not appear to change with colour. An aegirine-augite with $\alpha : c = 20°$ has been reported (Garson & Campbell Smith, 1958, p. 21).

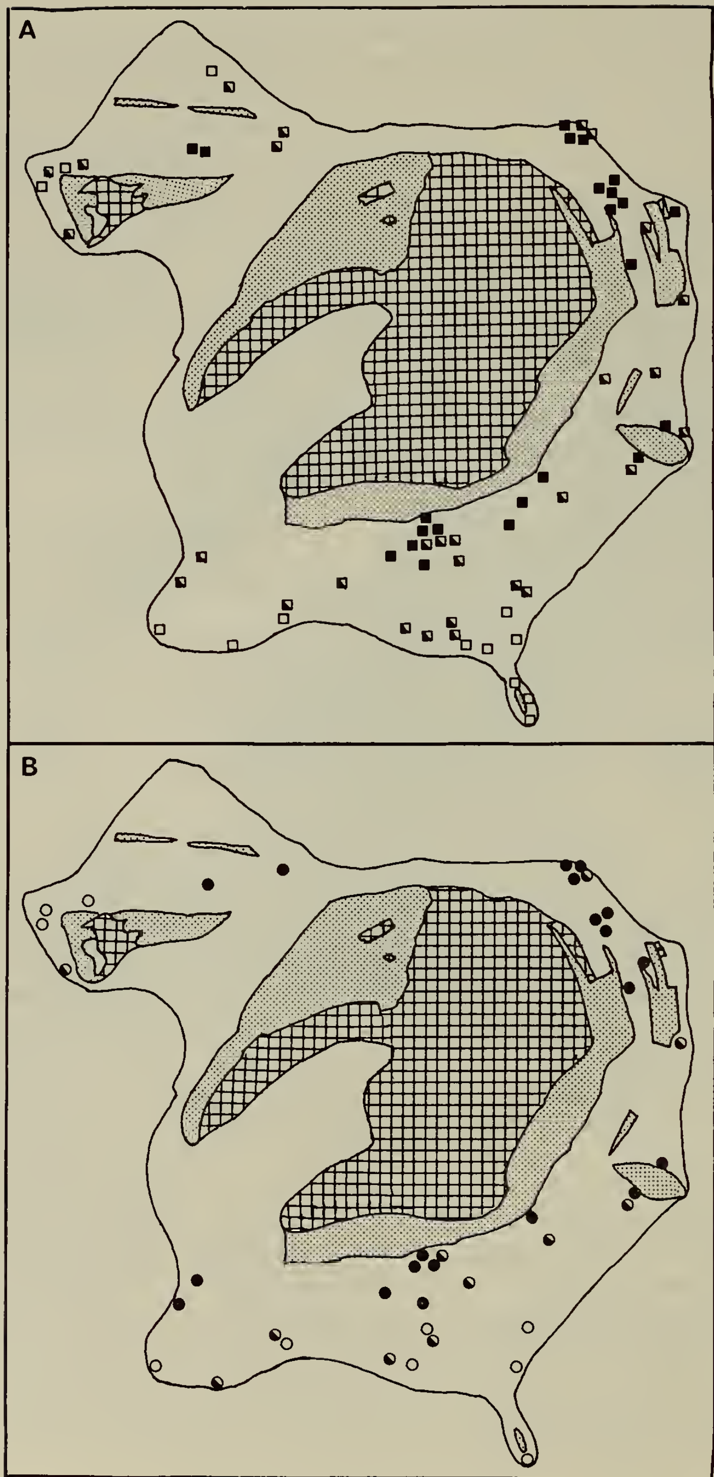



FIG. 3. (A) The distribution of syenitic fenites, quartz fenites, and lightly fenitized rocks on Chilwa Island, based on thin-section evidence. ■ = syenitic fenites; ◪ = quartz fenites; □ = lightly fenitized rocks. Squared ruling = carbonatite. Dots = felds-pathic breccia. (B) Distribution of alkaline amphiboles in Chilwa Island fenites. ● = pale blue amphiboles only (magnesioarfvedsonite); ◐ = mixed pale blue and riebeckitic amphiboles; ○ = riebeckitic amphiboles only.

Two distinct types of alkaline amphibole occur. One is a deep blue riebeckitic type which is confined to the outer fenite zone, particularly along the south coast of the island and pyroxene-bearing rocks on Chaone peninsula and at Marongwe and Chirunda Hills, in which it forms at the expense of ortho-pyroxene (Text-fig. 3B). The second amphibole is characteristically of a pale lilac colour and is almost universally present, though in small amounts, among clusters of aegirine grains in the syenitic fenites, and the inner zones of the quartz fenites; it is probably a magnesio-arfvedsonite (Deer *et al.*, 1962, p. 364). It is not certain whether there is a change in composition of the amphiboles with increasing fenitization in line with an increase of the oxidation ratio during fenitization, or whether the amphibole paragenesis is dictated by original rock composition. The optical properties of these amphiboles are difficult to determine because of the small size of the grains, deep colour, strong absorption or anomalous extinction. The riebeckite is pleochroic in shades of lilac, blue and buff e.g. $\alpha$ = deep blue; $\beta$ = pale yellow-buff; $\gamma$ = indigo-blue; $\alpha : c = 3°$. The paler amphibole has already been discussed at length (Dixey *et al.*, 1937, p. 18; Garson & Campbell Smith, 1958, p. 21). However, in the latter account, the extinction is described as small, but during the present work angles of $\alpha : c = 42–44°$ have been measured on many grains. An amphibole having a strength of colour somewhere between these two amphiboles and $\alpha : c = 30–35°$ sometimes occurs in the quartz fenites. The relative distribution of the amphiboles is shown in Text-fig. 3B.

Plagioclase, oligoclase to andesine, is the dominant feldspar in the basement schists and is important in the syenites. During fenitization it is transformed into a perthite as is the orthoclase. The course of this alteration is often well illustrated along the fine veins and cracks which traverse the feldspar. Along and adjacent to these veins a zone of turbidity develops, which gradually intensifies and spreads into the feldspar, while concomitantly the plagioclase twinning fades. The turbidity also spreads in from the feldspar margins, indicating that the crystal boundaries also were channels for fluid migration. Textural evidence suggests that the formation of the turbidity is probably associated with the removal of sodium from the feldspar, because several examples have been observed of narrow veins crossing feldspar, in which they cause turbidity, then, in crossing adjacent quartz grains promoting the growth of aegirine crystals. It appears likely that the sodium fixed in the aegirine has been transported along the vein from the feldspar. Narrow veins of carbonate have also been observed to generate turbid aureoles in plagioclase and to destroy the twinning. Orthoclase similarly becomes turbid early on in the fenitization. The syenitic fenites are dominated by a feldspar phase which often shows typical exsolution perthite textures, similar to those described from other fenite localities, e.g. Fen (Saether, 1957, fig. 4), and Alnö (von Eckermann, 1948, Plate 10, fig. 1). In the syenitic fenites formed from the porphyritic basement syenites the forms of the original feldspars are picked out by the turbidity, these turbid relics usually being surrounded by fresh rims of alkali feldspar which may be finely twinned. Some quite fresh albitic plagioclase and twinned microcline occurs in the syenitic fenites in the north-east corner of the Island near to Kotamu as a fine-grained granular mosaic insterstitial to the larger feldspars. This fresh, new feldspar appears to be associated, in general, with thick fenite veins of aegirine and potash-rich feldspar, but it could represent recrystallized material exsolved from the larger feldspars.

The mineralogical changes involved in the transformation of the syenitic fenites into the feldspathic breccias are relatively straightforward. The aegirine becomes unstable and breaks down to ore which, in contrast to the magnetite of the quartz and syenitic fenites, appears to be a mixture of haematite and limonite, while the feldspar, in which Carlsbad twinning is widespread and microcline cross-hatching occasionally to be seen, loses the perthite structures and becomes very much more turbid. Zircon is now quite abundant and quartz returns in the form of drusy infillings, which tend to be concentrated along lines of brecciation and narrow veins cutting the feldspars. Some varieties consist almost exclusively of potash-feldspar. The feldspathic breccias represent the ultimate stage of fenitization at Chilwa Island in so far as they lie adjacent to the carbonatite and are included as blocks within it.

The veins which cut the fenites are of two types: carbonate veins, which are probably direct emanations from the carbonatites; and the fenite veins proper. Within the carbonate veins phlogopite, barytes and anatase have been identified. The fenite veins vary continuously from hair-like cracks and lines of turbidity within the feldspars of the outermost fenites, via veins of aegirine as much as 0·5 cm. wide, to aegirine-potassium-feldspar veins up to 10 cm. thick in the syenitic fenites. The aegirine veins (Garson & Campbell Smith, 1958, fig. 3) cut cleanly across the rock-forming minerals but the narrower ones are often discontinuous, fading out and starting again quite haphazardly. As well as aegirine lesser amounts of magnetite, which is occasionally the sole vein mineral, and riebeckite in the quartz fenites and magnesioarfvedsonite in the syenitic fenites, are found. The coarser veins are built of selvages of acicular, deep-green aegirines and cores of microcline-microperthite. The growth of the aegirine perpendicular to the walls gives rise to a comb-structure. Carbonate, magnetite, quartz and bastnaesite may also be present. The remnants of the veins can be identified in the feldspathic breccias as linear concentrations of iron oxides.

*Kangankunde*

The fenitized rocks of Kangankunde have been sub-divided, for petrographic purposes, by Garson & Campbell Smith (1965*a*, p. 29) into an outer group of shock-zone fenites, and an inner group of permeation fenites. Adjacent to the main carbonatite centres the fenites have been mapped by Garson as " feldspathized fenites ", between which and the carbonatite " feldspathic breccia and agglomerate " has been distinguished (Text-fig. 4). The feldspathic breccia and agglomerate is equivalent to the feldspathic breccia and contact breccia at Chilwa Island. The process of feldspathization has been taken a stage further at Kangankunde however, by a process of phlogopitization (op. cit. p. 42), which is not found at Chilwa Island.

The fenitized rocks of Kangankunde show a number of marked differences from the fenites of Chilwa Island:

(1) A wider range of basement rocks come within the Kangankunde aureole,

including amphibolites, garnet and epidote amphibolites, meta-dolerites, hornblende-biotite gneisses, quartzo-feldspathic granulites, quartz reefs and granitic pegmatites, while the syenites, which occupy about half of the basement at Chilwa Island, are absent here.

(2) The lower grades of fenitization are fully represented at Kangankunde. At Chilwa Island this zone is mostly hidden beneath the lake.

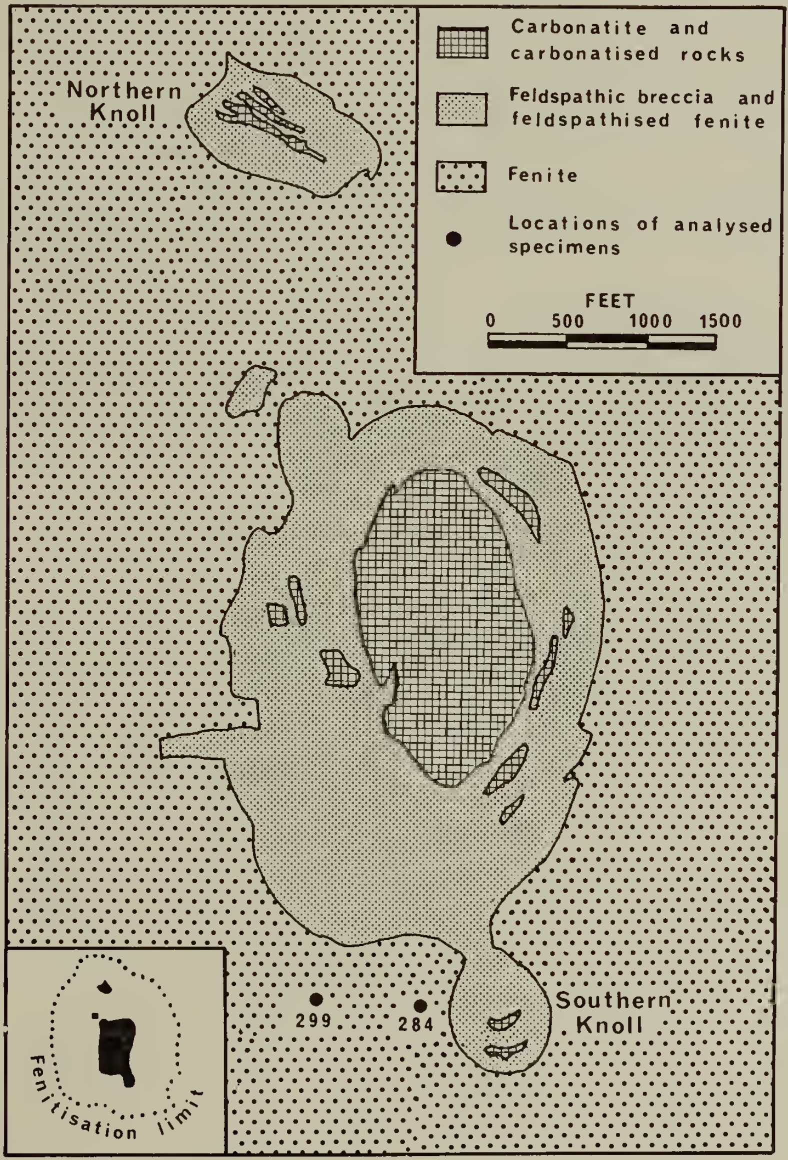



FIG. 4. Simplified geological map of Kangankunde based on map of Garson (1966, fig. 7). The locations of the analysed specimens are indicated.

(3) Fenitization proper (see p. 209) is not so intense at Kangankunde, as evidenced by the restricted occurrence of syenitic fenites.

(4) The oxidation of the ore minerals and the breakdown of aegirine and alkaline amphibole to hydrated iron oxides, which are characteristic of the feldspathic breccias of Chilwa Island, are more widespread at Kangankunde, and are often manifest well outside the zone of feldspathized fenites, as mapped by Garson.

(5) Primary quartz persists well into the feldspathic breccia and agglomerate.

(6) Alkaline amphiboles are more abundant in the Kangankunde than the Chilwa Island fenites. They appear to represent a greater range of compositions and have quite different textures to those of Chilwa Island.

(7) Carbonate is widespread. Some of the carbonate has resulted from the alteration of plagioclase, but most of it is concentrated along the centre of, and adjacent to, fenite veins, and a close correlation can often be demonstrated between these carbonate-bearing veins and the intensity of fenitization of the enclosing rock. Carbonate is usually only evident in the inner zones of fenitization at Chilwa Island.

(8) The coarse aegirine-potash-feldspar veins found at Chilwa Island have not been found at Kangankunde.

(9) Many of the feldspathic breccias of Kangankunde have been phlogopitized.

Many of the detailed mineralogical changes revealed by thin-sections of Kangankunde fenites are similar to those described for Chilwa Island. The basement plagioclases (oligoclase to andesine) are made over to an intensely turbid potash feldspar along veins and cracks and around the margins but the development of perthite textures, which characterize the syenitic fenite stage, has only been observed in a few specimens from the South-east side of the Fenite Spur (Garson, 1965*a*, Map No. 2). The primary hornblende, epidote, biotite, and garnet of the basement gneisses are gradually replaced by feldspar and altered to aegirine, alkaline amphibole and biotite. Whereas hornblende usually alters directly to aegirine in most Chilwa Island fenites, an intermediate fine-grained biotite stage is usual at Kangankunde. The primary biotite commonly persists into the feldspathic breccia stage. Alkaline amphiboles tend to be intergrown with aegirine and form fine-grained, fibrous, stellate, zoned masses in which the zoning may be defined by colour changes or by alternate layers of amphibole and aegirine. These masses replace quartz and mafic minerals and also form nodules and larger masses along fenite veins. Garson (1965*a*, p. 33) was able to distinguish, by optical means, riebeckite, crossite, magnesioarfvedsonite and soda-tremolite, often intergrown in a single mass (op. cit. fig. 3). The abundance of iron oxides, apparently in the form of limonite and goethite, is characteristic of the Kangankunde fenites, and in the higher zones of fenitization these completely replace the mafic minerals and extend as a coating to the feldspars. The breakdown of the mafic minerals is often strikingly promoted in the vicinity of carbonate concentrations, and carbonate is invariably abundant where phlogopitization of the potash-feldspar has taken place. The phlogopite development is most widespread in the feldspathic breccia and agglomerate and within xenoliths of these rocks in the carbonatite, but it can be observed also in the more carbonate-rich of the feldspathized fenites.

It is everywhere apparent in the Kangankunde fenites that the process of fenitization has been effected mainly through the agency of the fenite veins, although the extreme development of these veins, as represented by the thick aegirine-potash-feldspar veins of Chilwa Island, is not found at Kangankunde. The chemical changes which are associated with the early development of the fenite veins have been investigated with an electron probe. Some of the results are given as Plate 9. The photomicrographs show the way in which the multiple twinning of the plagioclase is destroyed along the veins and is replaced by a turbid, untwinned feldspar. Along the centre of the veins there is commonly a thread of aegirine. The probe traverses indicate that the turbid feldspar is strongly potassic, sodium being concentrated in the aegirine and plagioclase. The probe work also showed that the potash-feldspar is very much lower in calcium than the plagioclase. This alteration represents, on a small scale, the development of a syenitic fenite. The same process, on a hand specimen scale, is shown in Plate 9 B and C in which the altered feldspar zone is now a centimetre or more wide. This contrast constitutes the junction between the fenites and the feldspathized fenites, and for Chilwa Island is equivalent to the hidden contact between the feldspathic breccia and the syenitic fenites. Thin-sections across the fenite vein of Plate 9 B reveal that the inner part of the vein is built of turbid feldspar and ore—equivalent to the potash-rich feldspathic breccias; the outer parts of the vein contain abundant pyroxene, amphibole and turbid feldspar—equivalent to the syenitic feldspar stage, while the unaffected rock is a quartz fenite.

## THE CHEMISTRY OF FENITIZATION

In Table 1 are given the results of chemical analysis of 12 fenites and associated rocks from Chilwa Island and Kangankunde, the localities of which are shown on Text-figs. 2 and 4. When considering bulk chemical changes during fenitization it is probably advantageous to compare cationic concentrations on a standard oxygen cell. The case for this procedure has been argued fully by McKie (1966, p. 262) and following McKie the cationic concentrations per 100 oxygens are given in Table 2, and used for comparative purposes.

Of the Chilwa rocks, six are fenitized older syenites, one is a thick " fenite " vein and one a feldspathic breccia. The analysed fenitized syenites are now syenitic fenites composed dominantly of aegirine and perthite, with minor quartz, alkaline amphibole, carbonate, ore, secondary biotite and plagioclase, and quartz fenites containing appreciable quartz, and lesser amounts of hornblende and biotite, and in one specimen (No. 4) clinopyroxene. A suite of older syenites were chosen for analysis because these rocks are more homogeneous, prior to fenitization, than the very variable basement schists. The analysed fenite vein is 6 cm. thick and has selvages of deep-green, acicular aegirine forming radiating clusters, dominantly orientated perpendicular to the vein walls, and an interior composed of stubby, subhedral perthite plates up to 1 cm. across. Minor ore and sericite are present. The cream coloured feldspathic breccia consists of about 98 % potash-feldspar which is extremely turbid, as seen in thin section, and forms a granular mosaic and in places a vaguely defined trachytic texture of subprismatic, twinned grains. Ore and zircon are also present.

Garson (1965*a*, p. 124) has pointed out that because of the wide range of rock types in the Kangankunde aureole it is not practicable to obtain a series of chemical analyses of rocks to show the trend of fenitization. Therefore the two veined specimens illustrated in Plate 9 have been chosen as representing, on a small scale, the changes from the quartz fenite through to the syenitic fenite and feldspathic breccia stage. The main fenite rock and the veined parts were mechanically separated and both portions analysed. The specimens were found in dry stream beds on the south side of Kangankunde, west of the Southern Knoll (Garson 1965*a*, map 2). Neither specimen was *in situ*, but both probably come from the rocks mapped as " feldspathized fenites " by Garson, which occupy the higher slopes of the hill.

Rock B.M. 1968, P 37, 284 (analyses 9 and 10) is essentially a leucocratic quartz-feldspar granulite. Quartz comprises about 25% of the rock and the feldspar is mainly a sodic plagioclase, with some potash-feldspar. The feldspars are sericitized around the margins and along cleavages and cracks. A reddish biotite and magnetite are plentiful. The metasomatic fenite vein comprises a central thread of limonite or goethite, and an aureole surrounding this in which the feldspar is much more turbid than in the matrix fenite (Plate 9 B) and there is a great abundance of colourless to pale-green stellate clusters of aegirine needles. Quartz decreases within this aureole, and biotite is rarely found. The changes in the feldspar are vividly shown in places in which twinned plagioclase grains are sharply truncated by the veins, as previously described (Plate 9 A). The significant changes associated with the veining are, therefore, the decrease of quartz, development of aegirine, oxidation of the ore minerals and the change of the plagioclase to a potash feldspar. This overall transformation is consistent with the changes involved in going from a quartz fenite towards a syenitic fenite.

The changes along the vein of rock B.M. 1968, P 37, 299 (analyses 11 and 12) are even more profound, in so far as they appear to represent the transition from quartz fenite, through syenitic fenite to a feldspar-ore rock of feldspathic breccia type. The main rock is a plagioclase (oligoclase–andesine)–quartz–hornblende–biotite gneiss with minor garnet and ore, and some secondary aegirine and patchily distributed turbidity in the feldspars. The veins have a thin central thread of a hydrated iron oxide and a zone on either side, up to 2 cm. across, which is quite pink in the hand specimen, and in thin-section is characterized by the extreme turbidity of the feldspars. Within this zone there is a radical decrease in the quartz and no hornblende, biotite or garnet occur. Aegirine and secondary amphibole are abundantly developed along the outer edges of the turbid zone, the inner parts being dominated by feldspar and irregular ore patches. It would seem, therefore, that the metasomatic changes which define the presence of these veins represent, on a small scale, the variation from quartz fenites, through syenitic fenites, towards the extreme type of fenite consisting of potassium–feldspar and ore only.

The chemical analyses were made by A. J. Easton. $SiO_2$, $Al_2O_3$, CaO and MgO were determined gravimetrically on a sodium carbonate fusion, while the other oxides were determined on an acid ($HF/H_2SO_4$) dissolution using spectrophotometric and flame photometric methods.

An inspection of the Chilwa analyses in Tables 1 and 3 reveals immediately the extreme chemical differences between the quartz and syenitic fenites and the feldspathic breccia. The breccia is very much higher in $K_2O$ and lower in $Na_2O$, and is poor in $TiO_2$, $Fe_2O_3$, FeO and CaO. These changes are obviously to be expected from the mineralogy, but the field and microscope evidence suggesting that these

## Table I

Chemical analyses of fenites from Chilwa Island and Kangankunde

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 59·53 | 62·00 | 62·38 | 63·19 | 58·05 | 57·06 | 59·64 | 62·87 | 66·70 | 66·16 | 72·85 | 59·57 |
| $TiO_2$ | 0·95 | 0·97 | 0·77 | 0·82 | 1·16 | 1·53 | 0·52 | 0·02 | 0·22 | 0·29 | 0·21 | 0·28 |
| $Al_2O_3$ | 12·01 | 13·38 | 12·47 | 13·94 | 14·46 | 16·69 | 10·55 | 20·08 | 15·38 | 13·81 | 12·94 | 15·08 |
| $Fe_2O_3$ | 6·17 | 4·56 | 4·21 | 4·19 | 5·87 | 6·02 | 10·77 | 0·25 | 1·13 | 5·59 | 2·04 | 7·22 |
| $FeO$ | 1·45 | 1·60 | 2·10 | 2·20 | 1·09 | 3·61 | 1·14 | <0·05 | 1·75 | 0·31 | 1·40 | <0·05 |
| $CaO$ | 4·65 | 2·50 | 3·20 | 3·04 | 4·60 | 2·66 | 3·76 | 0·1 | 3·25 | 2·61 | 3·95 | 3·52 |
| $MgO$ | 1·31 | 0·90 | 0·70 | 0·93 | 0·94 | 0·99 | 0·56 | 0·80 | 1·18 | 0·80 | 0·73 | 0·41 |
| $MnO$ | 0·23 | 0·13 | 0·09 | 0·09 | 0·27 | 0·15 | 0·30 | <0·03 | 0·10 | 0·16 | 0·10 | 0·15 |
| $Na_2O$ | 7·61 | 8·05 | 8·18 | 4·45 | 6·40 | 5·24 | 4·12 | 0·49 | 4·52 | 4·65 | 3·35 | 3·47 |
| $K_2O$ | 4·66 | 4·71 | 4·70 | 4·88 | 4·65 | 3·56 | 8·28 | 14·11 | 2·13 | 2·61 | 0·88 | 6·69 |
| $P_2O_5$ | 0·33 | 0·42 | 0·40 | 0·36 | 0·53 | 0·79 | 0·06 | 0·23 | 0·18 | 0·20 | 0·10 | 0·50 |
| $H_2O^-$ | 0·1 | 0·1 | 0·1 | 0·1 | 0·2 | 0·1 | <0·1 | 0·2 | 0·2 | 0·3 | 0·2 | 0·3 |
| $H_2O^+$ | 0·2 | 0·4 | 0·4 | 0·4 | 0·7 | 0·6 | 0·3 | 0·5 | 0·5 | 0·9 | 0·4 | 1·1 |
| $CO_2$ | 0·5 | 0·8 | 0·8 | 1·3 | 1·2 | 0·5 | 0·2 | 0·2 | 2·5 | 1·2 | 0·5 | 1·5 |
| | 99·70 | 100·52 | 100·50 | 99·89 | 100·12 | 99·50 | 100·20 | 99·85 | 99·74 | 99·59 | 99·65 | 99·79 |
| $\left(\frac{100Fe^{3+}}{Fe^{2+} + Fe^{3+}}\right)$ | 80 | 72 | 64 | 66 | 83 | 60 | 90 | 100 | 37 | 94 | 57 | 100 |

1. Syenitic fenite (fenitized older syenite). Chilwa Island. (B.M. 1968, P 37, 37).
2. Quartz fenite (fenitized older syenite). Chilwa Island. (B.M. 1968, P 37, 85).
3. Quartz fenite (fenitized older syenite). Chilwa Island. (B.M. 1968, P 37, 96).
4. Quartz fenite (fenitized older syenite). Chilwa Island. (B.M. 1968, P 37, 100).
5. Syenitic fenite (fenitized older syenite). Chilwa Island. (B.M. 1968, P 37, 103).
6. Quartz fenite (fenitized older syenite). Chilwa Island. (B.M. 1968, P 37, 108).
7. Aegirine–potash–feldspar fenite vein. Chilwa Island. (B.M. 1968, P 37, 104).
8. Feldspathic breccia. Chilwa Island. (B.M. 1968, P 37, 71).
9. Quartz fenite. (fenitized quartz-feldspar granulite) Kangankunde. (B.M. 1968, P 37, 284).
10. Fenite vein cutting specimen 9. Above. Kangankunde. (B.M. 1968, P 37, 284).
11. Quartz fenite. (Fenitized quartz–plagioclase–hornblende–biotite gneiss) Kangankunde. (B.M. 1968, P 37, 299).
12. Fenite vein cutting specimen 11. Above. Kangankunde. (B.M. 1968, P 37, 299).

Numbers given in parentheses are the numbers of the specimens in the collection of the British Museum (Natural History).

Analyst A. J. Easton.

TABLE 2

Composition of the Chilwa Island and Kangankunde fenites in cations per 100 oxygen anions.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Si | 34·99 | 35·44 | 35·78 | 35·77 | 33·47 | 33·06 | 35·52 | 35·92 | 36·33 | 36·60 | 39·49 | 33·97 |
| Ti | 0·42 | 0·41 | 0·33 | 0·35 | 0·50 | 0·67 | 0·23 | 0·01 | 0·09 | 0·12 | 0·09 | 0·12 |
| Al | 8·32 | 9·01 | 8·43 | 9·30 | 9·83 | 11·40 | 7·41 | 13·52 | 9·87 | 9·01 | 8·27 | 10·14 |
| $Fe^{3+}$ | 2·73 | 1·96 | 1·82 | 1·78 | 2·55 | 2·62 | 4·83 | 0·11 | 0·46 | 2·33 | 0·83 | 3·10 |
| $Fe^{2+}$ | 0·71 | 0·76 | 1·01 | 1·04 | 0·53 | 1·75 | 0·57 | 0·00 | 0·80 | 0·14 | 0·63 | 0·00 |
| Ca | 2·93 | 1·53 | 1·96 | 1·84 | 2·84 | 1·65 | 2·40 | 0·06 | 1·90 | 1·55 | 2·29 | 2·15 |
| Mg | 1·15 | 0·77 | 0·60 | 0·78 | 0·81 | 0·85 | 0·50 | 0·68 | 0·96 | 0·66 | 0·59 | 0·35 |
| Mn | 0·11 | 0·06 | 0·04 | 0·04 | 0·13 | 0·07 | 0·15 | 0·00 | 0·05 | 0·07 | 0·04 | 0·07 |
| Na | 8·67 | 8·92 | 9·10 | 4·88 | 7·15 | 5·89 | 4·75 | 0·54 | 4·77 | 4·99 | 3·52 | 3·84 |
| K | 3·49 | 3·43 | 3·44 | 3·52 | 3·42 | 2·63 | 6·29 | 10·29 | 1·48 | 1·84 | 0·61 | 4·87 |
| F | 0·16 | 0·20 | 0·19 | 0·17 | 0·26 | 0·39 | 0·03 | 0·11 | 0·08 | 0·09 | 0·04 | 0·24 |
| $H^+$ | 0·78 | 1·52 | 1·53 | 1·51 | 2·69 | 2·32 | 1·19 | 1·90 | 1·82 | 3·32 | 1·45 | 4·18 |
| $H^-$ | 0·39 | 0·38 | 0·38 | 0·38 | 0·77 | 0·39 | 0·00 | 0·76 | 0·73 | 1·11 | 0·72 | 1·14 |
| C | 0·40 | 0·62 | 0·63 | 1·01 | 0·94 | 0·39 | 0·16 | 0·16 | 1·86 | 0·91 | 0·37 | 1·17 |

The columns are numbered as in Table 1.

TABLE 3

| | MW71 | MW135 | MW71 and MW135 are |
|---|---|---|---|
| %$Na_2O$ | 0·70 | 0·63 | feldspathic breccias |
| %$K_2O$ | 15·89 | 15·90 | from Chilwa Island |

rocks developed *in situ* from basement schists and syenites points to a very liberal redistribution of elements. The general chemical changes which have been recognized to be typical of fenitization are nicely shown by the analyses of Kangankunde fenites and the associated metasomatic veins. It must be stressed that the veins (analyses 10 and 12, Table 1) represent *in situ* alteration of rocks 9 and 11 (Table 1). The changes are consistent and reveal weight percentage decreases in $SiO_2$, FeO, CaO and MgO and increases in $TiO_2$, $Fe_2O_3$, MnO, $Na_2O$, $K_2O$, $P_2O_5$ and water. Although these changes are sometimes small, their constancy is telling. Of outstanding significance is the large increase in the oxidation ratio, and the increase of the potash to soda ratio. These two increases are particularly characteristic of the change from the syenitic fenites to the ultra-potassic rocks, the feldspathic breccias of Garson.

It has been found that the triangle Qz–Ne–Ks is a particularly useful one for following the changes in the felsic constituents during fenitization, anorthite being insignificant in most fenites. In Text-figs. 5, 6, 7 and 8, plots of fenites from Chilwa Island and Kangankunde, Alnö, and various other fenite localities are presented. The Alnö results (Text-fig. 5) are particularly revealing; the mobilized ultra-fenites of von Eckermann (1948, p. 43) have been excluded. The tie-lines link rocks collected along recognizable horizons in the basement by von Eckermann to show the progressive fenitization of rocks which it can reasonably be assumed were once chemically similar. Two stages of fenitization are brought out by the diagram; the initial change from saturated country rocks and quartz syenites to saturated syenitic fenites lying close to the Ab–Or join, then the persistent increase in the $K_2O/Na_2O$ ratio moving the plots towards the composition of orthoclase. If the Chilwa Island fenites are now considered (Text-fig. 6) they show a somewhat similar pattern varying from oversaturated quartz fenites to syenitic fenites plotting on the Ab–Or join. This change is less extreme than the Alnö one because unfenitized rocks are not found on Chilwa Island, and the older syenites, when unfenitized, are poorer in silica than the average schist or gneiss. The alteration of syenitic fenites to the feldspathic breccias is, however, more extreme than the potash enrichment at Alnö, as shown by the dashed line on Text-fig. 6: a reflection of the almost total removal of sodium from the system. The aegirine-feldspar vein from Chilwa Island plots, rather surprisingly, close to the orthoclase point indicating the co-existence of a potassium-rich feldspar with the soda-pyroxene. The Kangankunde analyses are joined by tie-lines which show the trend of alteration along the veins. Analyses 9 and 10 show only a slight bulk change but what change there is is similar to that at Chilwa Island. Analyses 11 and 12 represent a much more fundamental alteration from a quartz-rich rock to one which is only slightly oversaturated. These Kangankunde results must, however, be considered in the light of the fact that the changes in individual oxides reflect a trend which is more consistent with the change to a feldspathic breccia than to a syenitic fenite, while the microscopic evidence suggests that the veins are partly zoned from syenitic fenites through to potash–feldspar–ore rocks. Analysis 12, therefore, represents an admixture of syenitic fenite with potash–feldspar–ore rock, and reveals a trend which would be expected from such a hybrid.

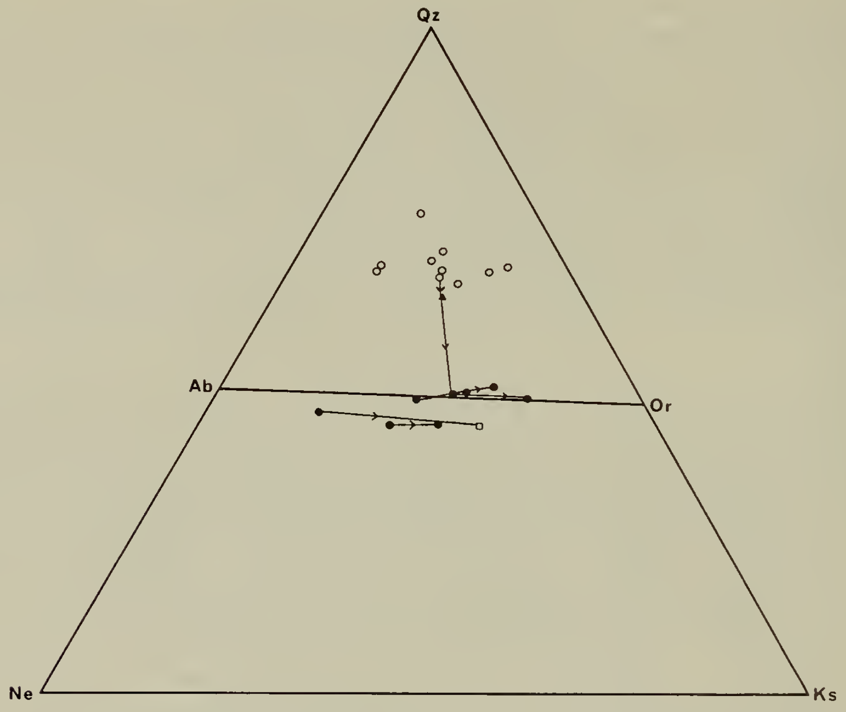



Fig. 5. Plot of fenites and associated country rocks of the Alnö Complex in the system Qz–Ne–Ks. Data taken from von Eckermann (1948, analyses 1–20). Tie lines join specimens collected along the strike. ○ = country rocks; ▲ = quartz fenite; ● = syenitic fenites; □ = nepheline-bearing fenites.

The chemical changes during fenitization in terms of the system Qz–Ne–Ks for a number of complexes, including Chilwa Island and Alnö, are given as Text-fig. 7. The lines represent trends shown by two or more analyses, and the dashed lines indicate the phase of potassium enrichment at Alnö and Chilwa. The majority of published fenite analyses are plotted on Text-fig. 8. Text-figs. 7 and 8 indicate an initial impoverishment in silica, then a certain amount of spread in the syenitic fenites between soda feldspar-bearing and potash feldspar-bearing rocks, the latter represented by the distinct trend towards the ultra-potassic rocks. It is noticeable that there is a slight concentration of syenitic fenite plots around the 35% potash-feldspar position on the Ab–Or join corresponding to the experimentally determined minimum for the alkali feldspars (Schairer, 1950). The trend lines of Text-fig. 7, with but two exceptions, radiate from the quartz apex indicating that there is little change in the bulk composition of the feldspars during fenitization, the total increase of sodium being partly held in the pyroxene. On Text-fig. 8 a few nepheline fenites are shown.

That there is an increase in alkalis during fenitization has long been realized and this is brought out well in Text-fig. 9 in which the trend of alkali enrichment, concomitant with a decrease of silica during the fenitization, is almost perpendicular to

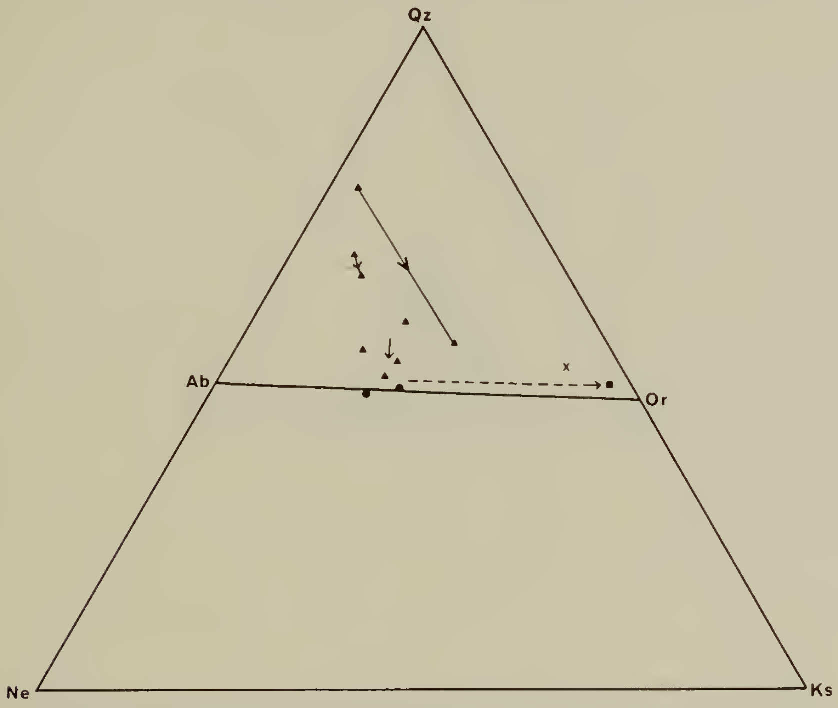



FIG. 6. Plot of Chilwa Island and Kangankunde fenites in the system Qz–Ne–Ks. The analyses of Kangankunde quartz fenites and the associated cross-cutting fenite veins, are joined by tie lines. ▲ = quartz fenites; ● = syenitic fenites; ■ = feldspathic breccia; × = aegirine–potash–feldspar fenite vein. Dashed arrow indicates path of feldspathization.

the alkali–silica relationship for normal rock series. The Chilwa Island and Kangankunde results conform to the trend, the latter being joined by tie lines which show the extreme alkali enrichment and silica impoverishment of analysis 12 in relation to 11. At the left hand end of the normal rock series on Text-fig. 9 are plotted a gabbro and a basalt and their fenitized equivalents, taken from Mathias (1956, Table 4). These plots show that the general tendency of alkali enrichment holds for basic as well as acid fenitized rocks, although the change in silica is now insignificant.

As well as an inverse relationship between silica and alkalis during fenitization there is a similar relationship between silica and iron, magnesia, and lime which is brought out in Text-fig. 10, and applies at Chilwa Island and Kangankunde. There is an increase of all three elements, although in general the increase in iron is the most substantial. Because of the abnormal increase of alkalis during fenitization the increase of total iron, magnesia, and lime is less than for a normal rock series showing a similar decrease of silica, and this is shown in Text-fig. 10 in which the normal trend is indicated by the dashed line. The low values for the feldspathic breccias are apparent.

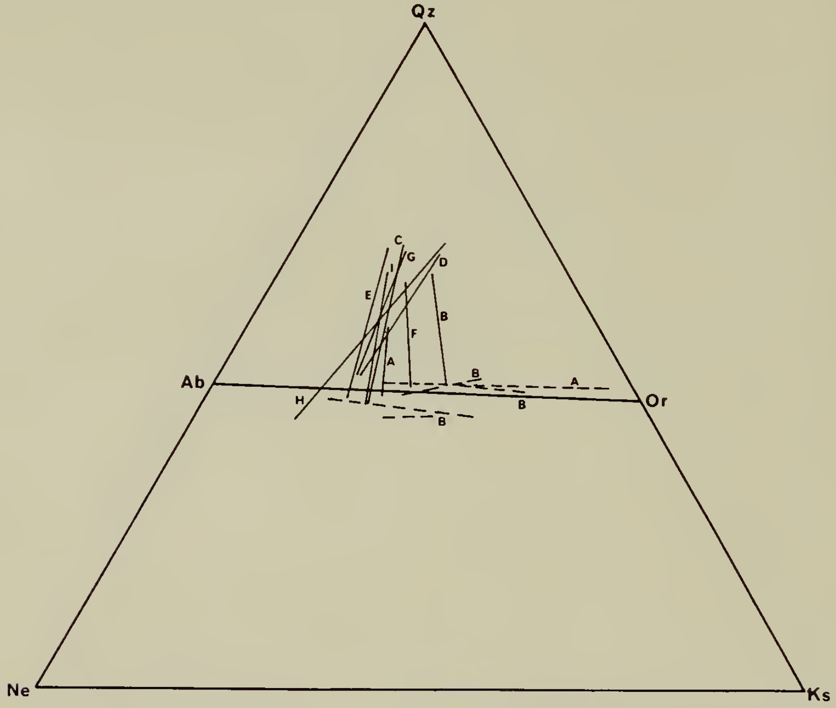



FIG. 7. The trend of fenitization at various localities plotted in the system Qz–Ne–Ks. The dashed lines trace the trend of potash enrichment at Chilwa Island and Alnö. A = Chilwa Island (8 analyses); B = Alnö (von Eckermann, 1948—20 analyses); C = Oldoinyo Dili (McKie, 1966—12 analyses); D = Norra Kärr (Adamson, 1944—2 analyses); E = Chishanya (Swift, 1952—3 analyses); F = Fen (Saether, 1957—3 analyses); G = Iivaara (Lehijärvi, 1960—2 analyses); H = Spitzkop (Strauss & Truter, 1951—10 analyses); I = Dorowa (Johnson, 1961—4 analyses).

It has been shown by several workers that there is an increase in the oxidation ratio ($Fe^{3+}/Fe^{3+} + Fe^{2+}$) during fenitization (von Eckermann 1948, p. 32; Verwoerd, 1966, p. 136; McKie, 1966, p. 278), ascribed by von Eckermann to the oxidizing action of $CO_2$ emanating from the carbonatite. The Chilwa Island and Kangankunde rocks conform very much to this pattern (Text-fig. 11) as shown by the increasing oxidation ratio of the Chilwa Island fenites, the higher value still of the fenite vein, and the characteristic total absence of ferrous iron in the feldspathic breccias. The high oxidation ratios revealed by the analyses of the Kangankunde vein rocks indicates that they have been subjected to chemical changes more akin to those which promote the development of the feldspathic breccias than the syenitic fenites.

## DISCUSSION

Before considering some of the genetic aspects of fenitization in the Chilwa Series, some clarification of the nomenclature of fenites, as used in this account, is needed. Three quite distinct major processes, and a number of minor ones, are commonly

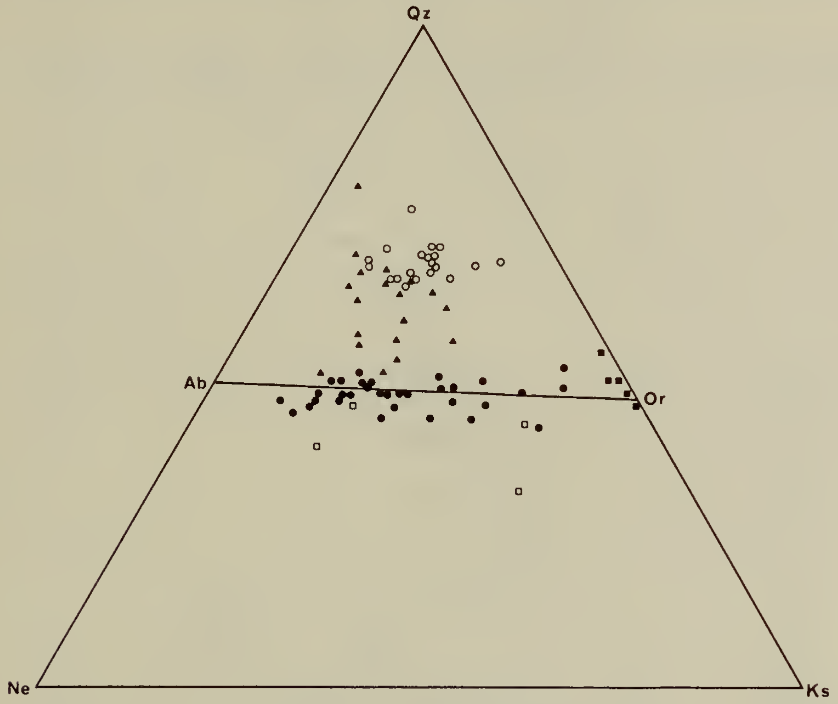



Fig. 8. Composite plot of fenite analyses in the system Qz–Ne–Ks. ○ = country rocks; ▲ = quartz fenites; ● = syenitic fenites; ■ = ultra-potassic fenites; □ = nepheline-bearing fenites.

referred to the omnibus term fenitization, and certain aspects pertaining to the nature of these three branches of fenitization can be illustrated by Text-fig. 12. This diagram has been constructed from the data presented in Text-fig. 8, which incorporates a high proportion of the chemical data on fenites published to date. On Text-fig. 12, three metasomatic processes are considered: fenitization proper; feldspathization (as used by Garson & Campbell Smith, 1958), and nephelinization. It seems reasonable to distinguish these three processes because each one is chemically and mineralogically distinctive, and, as will be discussed shortly, they are often associated with different groups of magmatic rocks:—

Fenitization is promoted by syenites, nepheline syenites, ijolites, carbonatites.

Nephelinization is promoted by nepheline syenites, ijolites, carbonatites(?).

Feldspathization is promoted by carbonatites.

Chemically the three processes, as they apply to granitic rocks (granites, gneisses and schists), are characterized as follows:

Fenitization = decrease of Si (from oversaturated to saturated rocks) increase of Na, K, Fe, Mg, Ca, Ti, and P and gradual increase of oxidation ratio.

Nephelinization = decrease of Si (from saturated to undersaturated rocks)—chemical data then uncertain, but probable increase of alkalies.

Feldspathization = sharp increase of oxidation ratio towards 100; radical increase of $K_2O$: $Na_2O$ ratio; decrease of Fe, Mg, Ca.

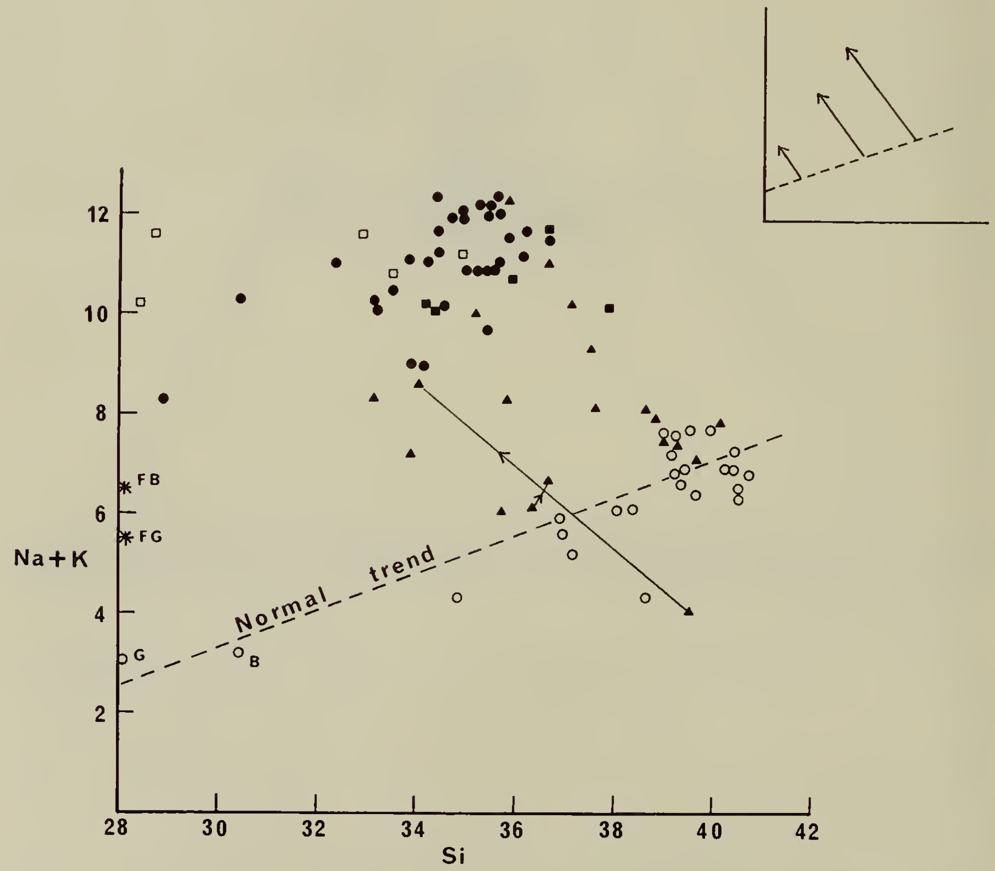



FIG. 9. The variation of alkalis (Na + K) and silica during fenitization, based on a cell of 100 oxygens. The main trend is indicated on the small inset diagram. The dashed line represents the variation of alkalis and silica for a normal rock series. Symbols as in fig. 8. B = basalt; G = gabbro; FB = fenitized basalt; FG = fenitized gabbro: from Messum Complex (Mathias, 1956). Tie lines join plots of Kangankunde veined fenites.

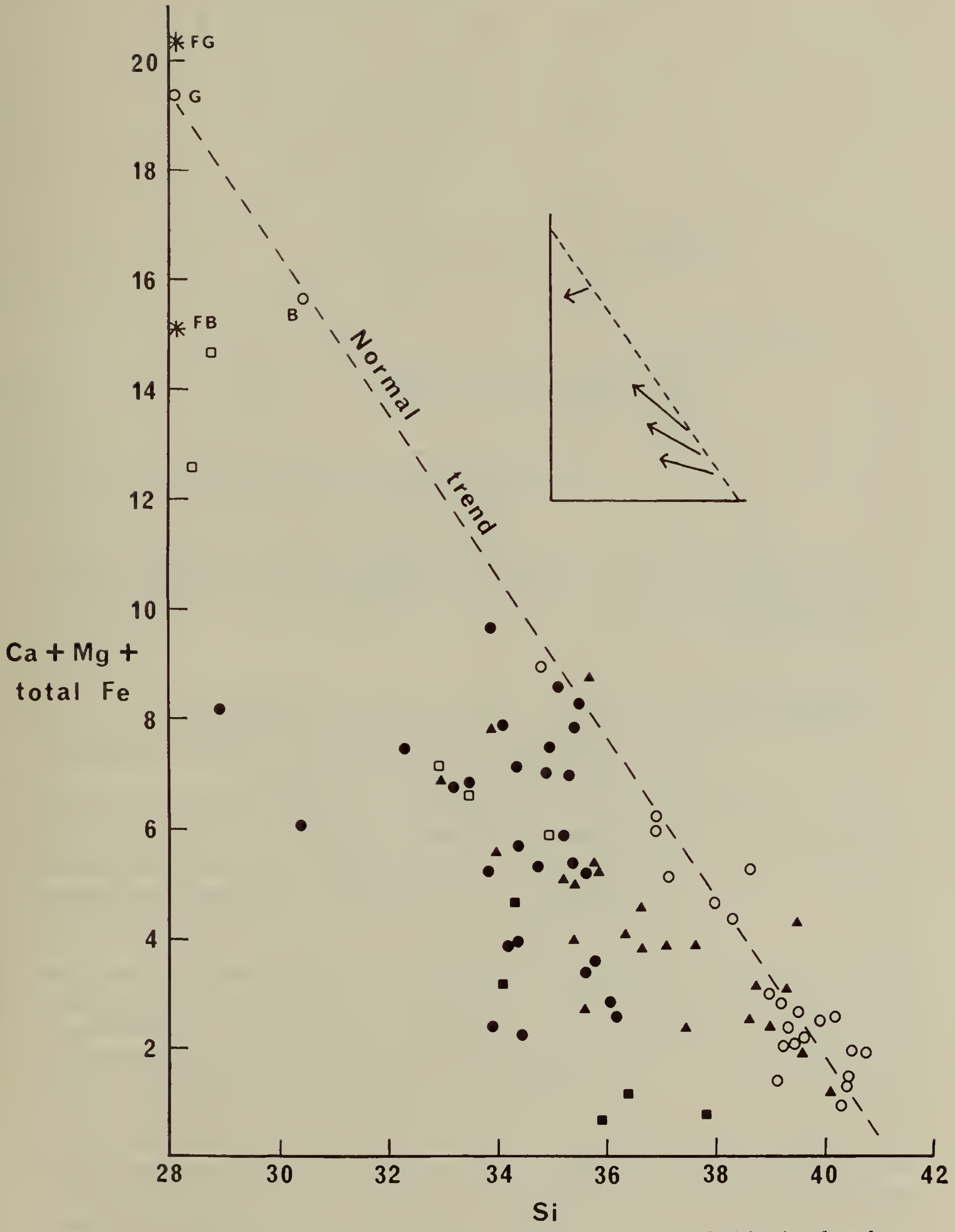



FIG. 10. The variation of (Ca + Mg + total Fe) against silica during fenitization, based on a cell of 100 oxygens. The principal trend is indicated on the small inset diagram. The dashed line indicates the trend for normal rock series. Symbols are as on fig. 8.

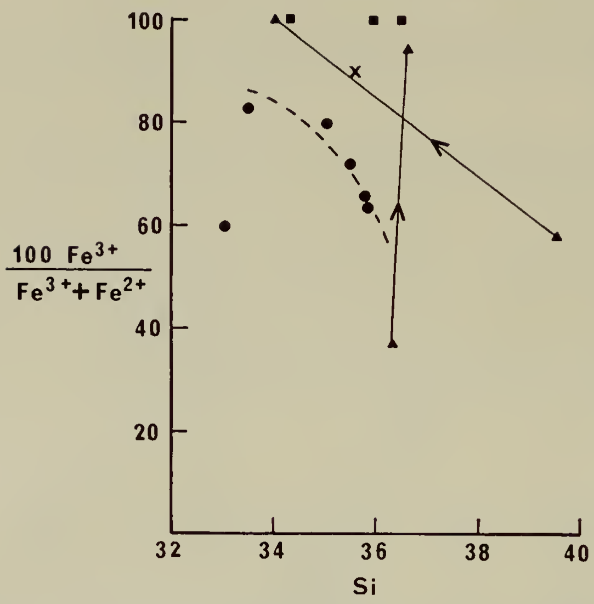



FIG. 11. Variation of the oxidation ratio (100 $Fe^{3+}/Fe^{3+} + Fe^{2+}$) with the change in silica content for Chilwa Island and Kangankunde (Table 1). ● = Chilwa Island fenites; ▲ = Kangankunde fenites; × = aegirine–potash–feldspar fenite vein, Chilwa Island; ■ = feldspathic breccia Chilwa Island and two feldspathic breccias from the Tundulu Complex (Garson, 1962, p. 79).

These chemical changes reflect the following mineralogical changes—

Fenitization = loss of quartz, growth of sodic pyroxene and amphibole, increase of alkali feldspar, resulting in perthitic syenite with alkaline mafics (i.e. aegirine, sodic amphibole).

Nephelinization = growth of nepheline at the expense of feldspar, with the production of a nepheline syenite.

Feldspathization = breakdown of sodic pyroxene and amphibole, alteration of alkali feldspar to potash-feldspar. Production of an ultra-potassic syenite.

The three processes are easily distinguished but many localities have been described, including Chilwa Island and Kangankunde, at which two or even three of these changes are contiguous, that is fenitization grading into nephelinization and fenitization grading into feldspathization, while fenitization and feldspathization may occur independently. A particular difficulty which arises in considering these three metasomatic processes however, is in deciding how much of the fenitization and nephelinization is caused by the carbonatite, a problem that has been discussed by King & Sutherland, (1960, p. 714). Because of the lack of large masses of silicate rocks in the Chilwa Island and Kangankunde complexes it would at first appear that all the metasomatic effects must be attributed to the carbonatite, and this is Garson's conclusion with regard to the Kangankunde complex (1965*a*, p. 123).

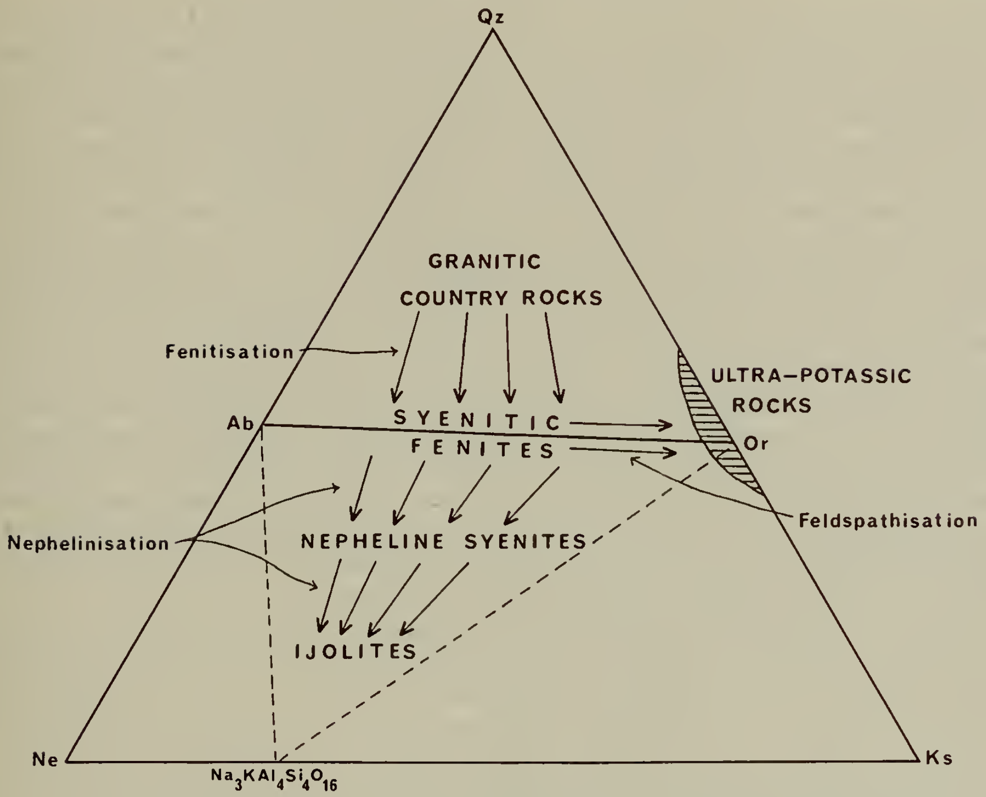



FIG. 12. Generalized diagram to show the principal chemical changes during fenitization, feldspathization and nephelinization, as they can be represented in the system Qz–Ne–Ks.

Dawson in his discussion of this very problem (1964, p. 108) cites Chilwa Island as a locality at which the fenitization is indubitably attributable to the carbonatite. Although this may be correct there is every reason to suppose that the Chilwa and possibly the Kangankunde complexes are sub-volcanic. As such, a pipe, now occupied by carbonatite, almost certainly was once a volcanic conduit facilitating the passage of strongly alkaline, undersaturated magmas to the surface. These magmas, which were probably phonolitic and may be represented by the Lupata Gorge volcanics occurring some 140 miles to the south-west (Dixey & Campbell Smith, 1929), were probably capable of fenitizing the walls of the pipe. This certainly applied to many of the circular or oval, sub-volcanic carbonatite complexes, which at their present erosion level reveal little, or no, silicate rock, but which have a fenite aureole. The metasomatic changes at Chilwa Island, Kangankunde and other Malawi centres which are undoubtedly attributable to the carbonatite are the feldspathization, which Garson has shown by his mapping at Kangankunde forms collars around the carbonatite pipes (Garson, 1965*a*), and the process of phlogopitization at Kangankunde. In an attempt to decide this issue the contacts of carbonatite bodies where there was definitely no influence from silicate magma must be considered. One such carbonatite is that at Songwe Scarp, described by Brown (1964, p. 223). The main contact effect according to Brown is a pronounced potash feldspathization of the adjacent schists; a marked increase in the oxidation ratio is also apparent from the analyses (op. cit. Table 3). Similarly the Rufunsa carbonatites (Bailey, 1960) only potash-feldspathize the country rocks, there is no sodic pyroxene or amphibole development. Fenitization of granites by beforsite dykes at the confluence of the Elands and Crocodile Rivers, Transvaal has been described by Fockema (1953, p. 155) but in fact the fenitized rocks consist of feldspar, quartz, chlorite and hydrated iron oxides, and analyses reveal a very high potash to soda ratio, suggesting feldspathization rather than fenitization. In contrast to these localities where an alteration akin to feldspathization rather than fenitization prevails, von Eckermann has found a definite increase of fenitization around sovite dykes at Alnö (1948, Pl. 59). The same feature is apparent at Tundulu (M. S. Garson; personal communication). These contrasting examples suggest either that there are a range of carbonatite magmas having strongly contrasting metasomatizing capabilities, perhaps related by an evolutionary sequence of changes in alkali content, or that a phenomenon of differential zonation related to contrasting rates of loss of Na and K from the magma occurs, or yet again that the fenitizing ability of carbonatite is dictated by the prevailing physico-chemical conditions.

It has been realized for some time that fenitization is not restricted to carbonatite complexes, and is to be found around nepheline syenite and ijolite bodies. Even saturated syenites are capable of fenitization as evidenced by the introduction of alkalis into Moine Schists around the Cnoc nan Cuilean intrusion, Sutherland, Scotland, resulting in the growth of aegirine-augite, as described by King (1943, p. 147). Garson has described fenitization effects around syenite bodies in the South Mlanje Area of Malawi (1963, p. 12) with the development of aegirine-augite in the altered country rocks. Syenites are only capable of promoting fenitization, that is alteration towards saturated rocks—syenitic fenites, but the nepheline syenites and ijolites are capable of desilicating the enclosing rock envelope—nephelinization. These changes are brought out in Text-fig. 12 and it is obvious that in terms of Qz–Ne–Ks the metasomatic changes are such as to make the altered rock over to a composition near to that of the active intrusive rock, so that the composition of the original material is not particularly significant.

It seems very unlikely that nephelinization can be caused by carbonatite, although at Alnö von Eckermann interprets the undersaturated rocks as hybrids produced by the interaction of carbonatite and other rocks (1948). The nephelinization at Tundulu has been shown by Garson to be related to the main ring-dyke of foyaite (1962, p. 61), while at Dorowa the nephelinized fenite (pulaskitic fenite) surrounds a body of foyaite and ijolite (Johnson 1961, p. 106). The inclusion of blocks of feldspathic breccia in carbonatite at Chilwa Island and Kangankunde indicates that the carbonatite was incapable of nephelinization, at least at this level. Inclusions of potash feldspar have been described from many carbonatites, indicating its stability in some carbonatite magmas.

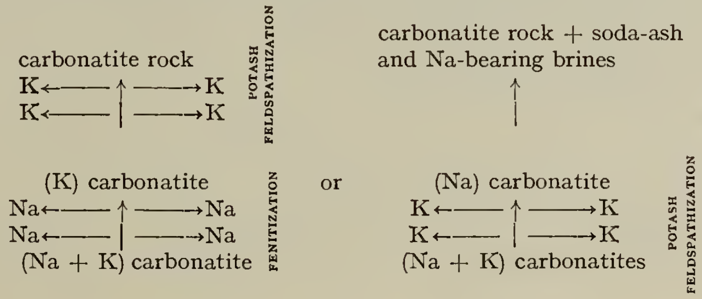
The process of phlogopitization at Kangankunde is shown by Garson & Campbell Smith (1965*a*, p. 44) to be a hydrothermal process involving the addition of MgO and water from ankeritic carbonatite, to potash feldspar. This process is not apparent at Chilwa Island, probably because the ankeritic carbonatite is insulated from the fenites by the earlier sovite. A similar process took place at Fen as can be seen in rocks on the W. side of the entrance to Hydro's quarry where blocks of fenite, enveloped in carbonatite, have reaction rims of phlogopite. The intermediate process of potash-feldspathization is not, however, manifest in the Fen rocks.

Before considering the relative importance of fenitization, nephelinization and feldspathization further it is appropriate to look at the chemical evidence from the Oldoinyo Lengai carbonatite lava (Dawson 1962, 1966; DuBois *et al.*, 1963). Analyses of this lava give $K_2O = 6{\cdot}5$–$7{\cdot}6\%$ and $Na_2O = 29{\cdot}0$–$30{\cdot}0\%$ (Dawson, 1966, Table IV). Analyses of plutonic carbonatite rock show an average total alkali content of less than 2%, with the notable feature that $K_2O$ is much greater than $Na_2O$ (Heinrich, 1966, Table 8–2). It seems very probable that most carbonatite magmas were at least as well endowed with alkalis as the Oldoinyo Lengai lava but that these alkalis were lost to the aureole during emplacement. The Oldoinyo Lengai carbonatite obviously has considerably more soda to contribute to the country rocks than potash, so that the highly potassic metasomatism associated with the carbonatites of Chilwa Island, Kangankunde and other Malawi carbonatite complexes, Songwe and Rufunsa presents a problem. Bailey suggests (1966, p. 150) that at Rufunsa the lack of soda may be an intrinsic property of the magma, or that at low temperatures soda may be unreactive with the wall rocks and hence is expelled at the surface in hot brines and as soda-ash. In considering the Malawi complexes in which fenitization and feldspathization occur two possibilities present themselves.

(a) An alkali-rich carbonatite was emplaced and the soda was lost preferentially, fenitizing the country rocks; the larger potash ions were then expelled and fixed in an inner zone of potash-rich rocks. That is differential zonation.

(b) The fenites were formed through the agency of silicate magmas in a central volcanic pipe, and the feldspathization was then superimposed on these by the later emplacement of the carbonatite. The potash metasomatism generated by the carbonate could be due either to the fact that potash was the only alkali available in the carbonatite, or that soda was held back and then expelled at the surface, as suggested by Bailey.

If the second variation is accepted it suggests that there are a range of carbonatite types; those, possibly primary ones, containing abundant soda and potash, and a series derived from these of potash-rich and soda-rich carbonatites. i.e.

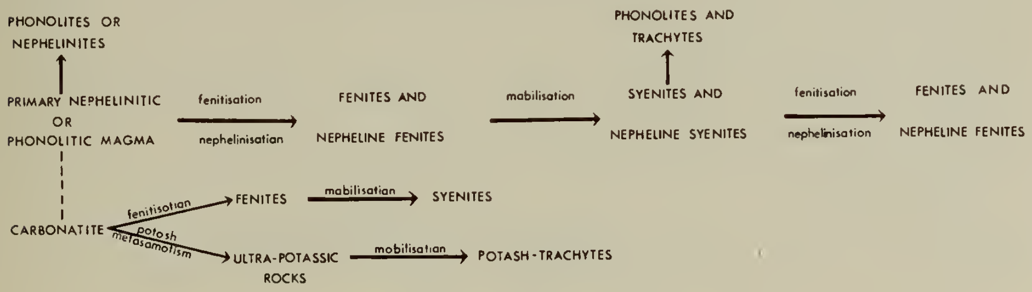


Presumably alkalis would be lost continuously within the higher levels of the crust and the " metasomatizing power " and character of the metasomatism would be determined by crustal level, proportion of the alkalis present, and the contrasting physico-chemical properties of the migrating potassium and sodium ions. Some carbonatite bodies have had very little effect on their immediate surroundings, so it is probable that these represent the last passive carbonatite fraction after the alkalis have been lost.

It is apparent that the Chilwa Island and Kangankunde fenitized and feldspathized rocks may have been generated by the differential zonation around an alkali carbonatite of Oldoinyo Lengai type, but that the mechanism whereby the fenitization is caused by a silicate magma and the ultra-potassic rocks by carbonatite is also quite feasible. There does not at the present time appear to be any reliable criterion to distinguish the two mechanisms, as they have applied in the Chilwa Province.

The microscopic evidence of Chilwa Island and Kangankunde fenites provides an abundance of evidence as to the actual mechanics of the fenitization process. Element migration was facilitated by veins, grain boundaries and cracks and cleavages in the minerals as shown by the distribution of the turbidity in the feldspars and the patterns of sodic pyroxene and amphibole growth. It would appear that migration took place principally in a fluid phase probably rich in water and $CO_2$ and that silica and alkalis were the principal migrants, though the threads of ore along many fenite veins attest to the mobility of iron. The metasomatic movements appear to have been on three levels: a short range movement within single grains, or between adjacent grains; a redistribution of material within the aureole as a whole, and a larger scale overall removal from, or addition to, the aureole. Small scale movement is exemplified, for instance, by the growth of aegirine at the expense of quartz with the soda being derived from adjacent plagioclases. Migration within the aureole is suggested by the impoverishment of the feldspathic breccias in iron, magnesium and sodium, while these elements accumulated in the normal fenitized rocks. The largest scale of movement involves the wholesale loss of silica from the system and the enrichment in alkalis; there has probably been an overall increase also in phosphorus and titanium. The silica loss provides the greatest problem with regard to its ultimate destination. Was it driven outwards, inwards or upwards? Von Eckerman suggests that at Alnö the silica migrated inwards into the carbonatite (von Eckermann, 1948). A combination of inward and upward movement seems the most likely, the silica perhaps being carried up a central volcanic pipe incorporated in silicate magma, or carried in solution to the surface in brines. The late silicification of the feldspathic breccias suggests that this means of egress from the system was closed when the carbonatite was emplaced.

The mobilization of fenites has been cited from several localities, for instance Alnö (von Eckermann, 1948, p. 27), and Semarule (King, 1955), and of mobilized ultra-potassic rocks from Chilwa Island (Garson & Campbell Smith, 1958, p. 29), Tundulu (Garson, 1962, p. 74) and Toror (Sutherland, 1965). Most of the intrusive silicate rocks at Alnö, nepheline syenites and ijolites, are ascribed to the mobilization of " ultrafenites " by von Eckermann. King & Sutherland (1960, p. 719) have evolved a scheme based on observations of East African alkaline rocks and carbonatites according to which mobilized fenites were emplaced as nepheline syenites and syenites, with equivalent extrusive phases of phonolite and trachyte. The Chilwa Alkaline Province is not restricted to the suite of carbonatites and closely associated rocks but also includes substantial plutons of syenite, Mlanje and Zomba Mountains, and nepheline syenite, Chikala, Chaone and Mongolowe Hills (Bloomfield, 1965, p. 96; Garson, 1963), which are closely associated in space and time with the carbonatites. The only extrusive rocks found in the main area of the Chilwa Province are small patches of thermally metamorphosed basic rocks on Chikala Hill (Stillman & Cox, 1960, p. 102). A chemical analysis of a porphyritic variety proved to be similar to the average nepheline tephrite (op. cit. Table 1). Some 140 miles to the south-west of Lake Chilwa a volcanic succession is exposed along the Lupata Gorge of the Zambezi, consisting of rhyolites, phonolites, kenytes, blairmorites (phonolites containing primary analcite) and tuffs, and these are intruded by nepheline syenite, microfoyaite and tinguaite (Dixey & Campbell Smith, 1929). This succession is cut by the Muambe carbonatite (Dias, 1961). The Muambe Complex belongs to the Chilwa Province and the alkaline lavas are very probably an extrusive phase consanguineous with the Chilwa Series. It is suggested that the relationship between the carbonatites, the nepheline syenites, syenites and volcanics may be as follows:

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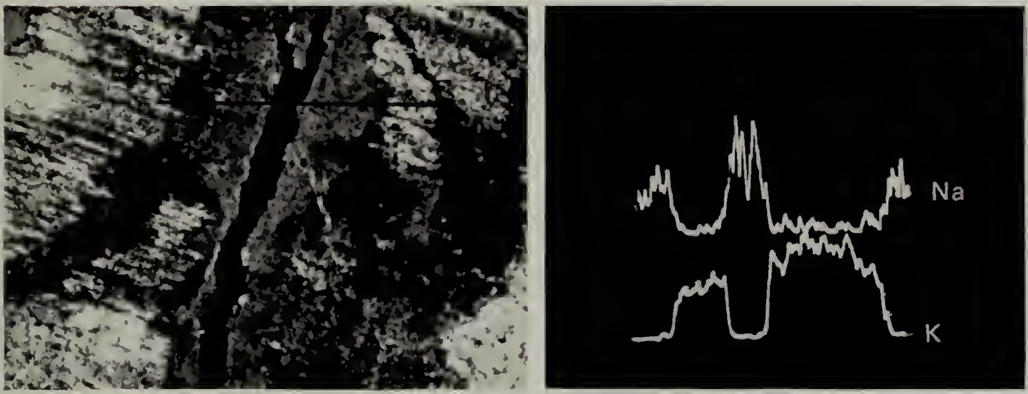
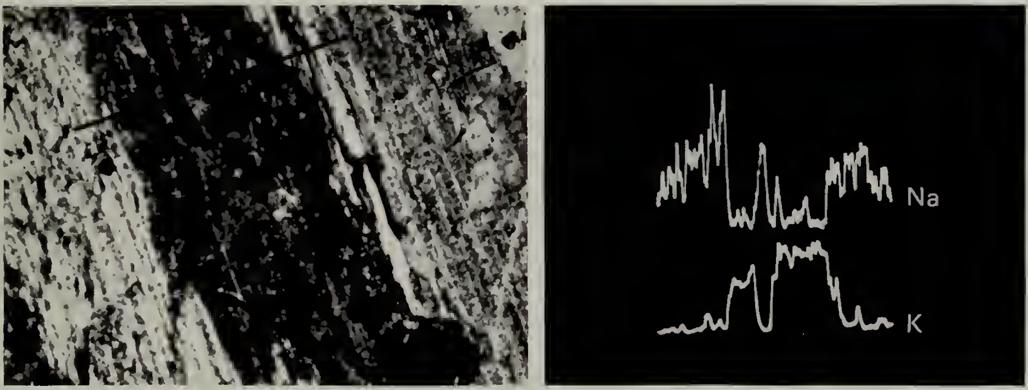
## PLATE 9

A. Electron probe traverses across veins of fenitization in plagioclases of a Kangankunde fenite (B.M. 1968, P 37, 267). Along the veins the plagioclase twinning is destroyed and a new turbid feldspar develops. The probe traverses, the paths of which are indicated by the ruled lines on the photomicrographs, show that sodium is concentrated in the unaltered plagioclase and in the central part of the veins, which is occupied by aegirine. The new turbid feldspar is poor in sodium and rich in potassium. The scale bar between the photomicrographs is 0·05 cm. long.

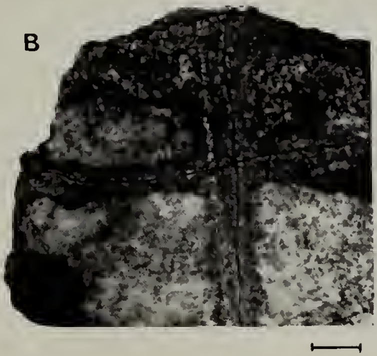
B and C. Kangankunde fenites cut by feldspathization veins {(B = B.M. 1968, P 37, 284; C = B.M. 1968, P 37, 299)}. The central black, thin thread in each case is predominantly limonite while the bordering feldspathized area is pink in colour, in contrast to the black and grey mottled fenite. The scale lines are 1 cm. long. The veined and unveined parts of these rocks were mechanically separated and chemically analysed (Table 1, analyses 9–12).




A




B



C